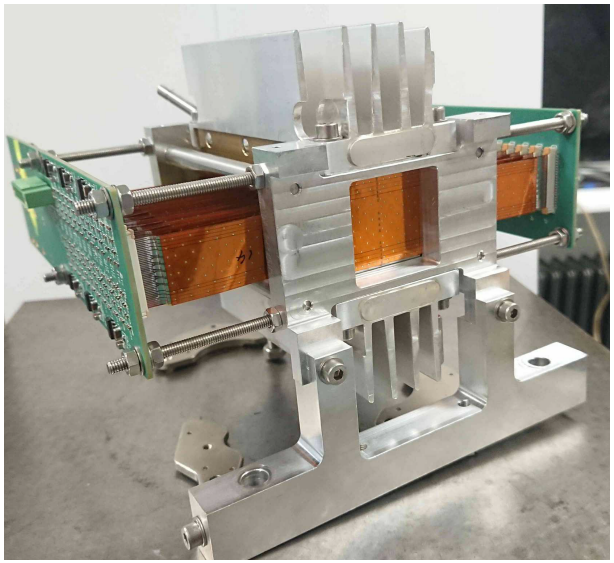
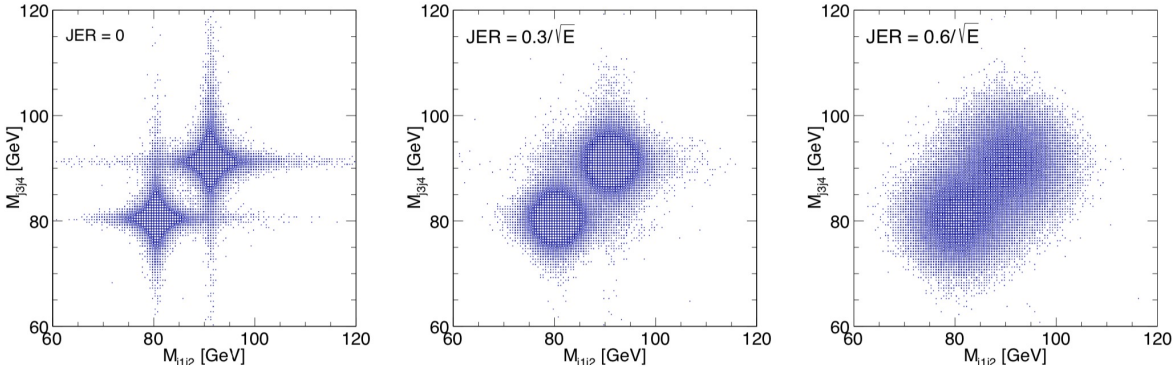
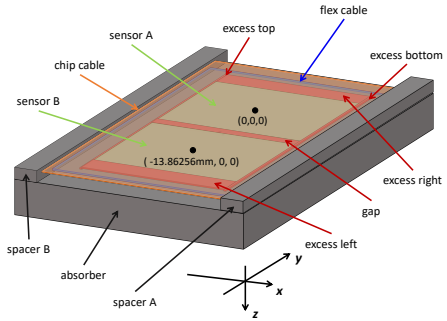
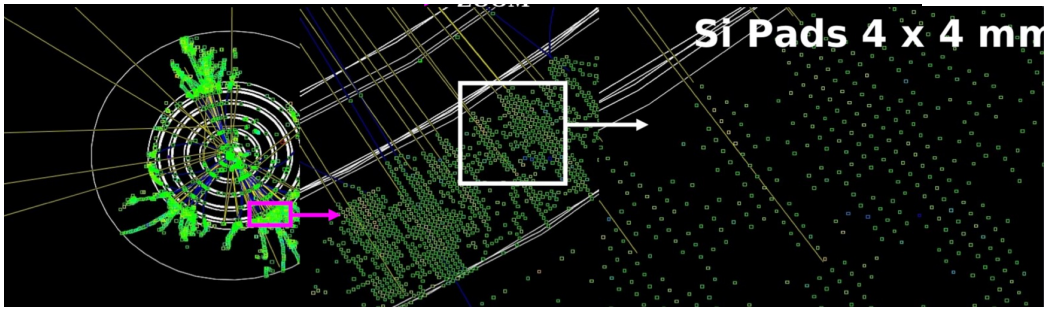
Recent progress and future plans for ultra-high granularity CMOS ECAL

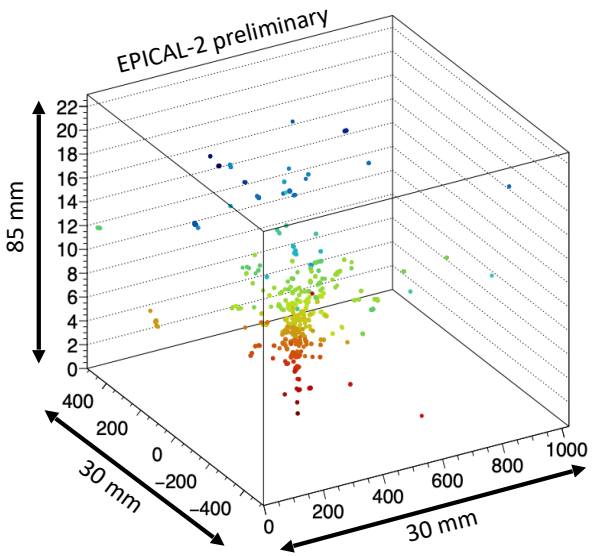
- Nigel Watson (Birmingham)





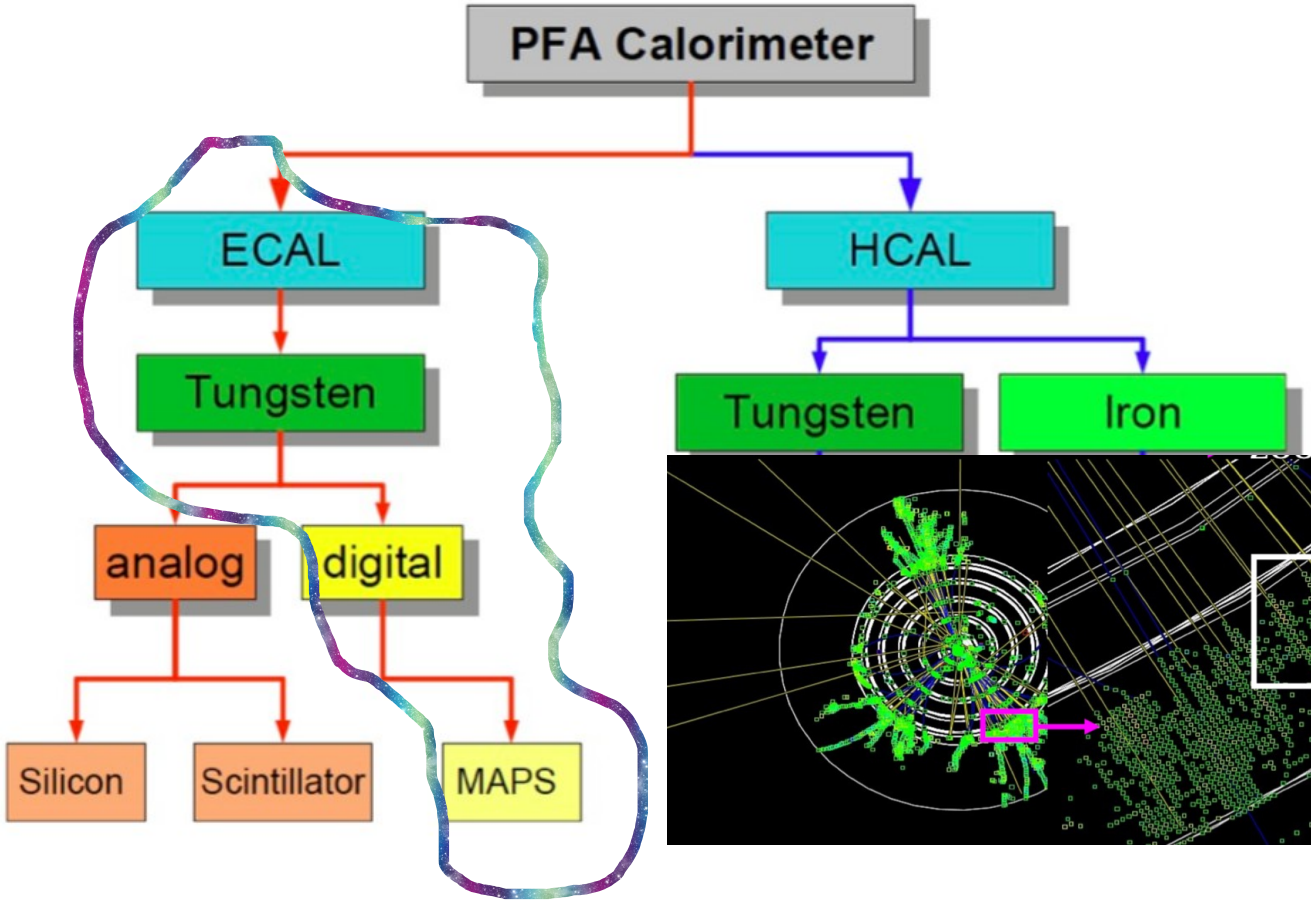


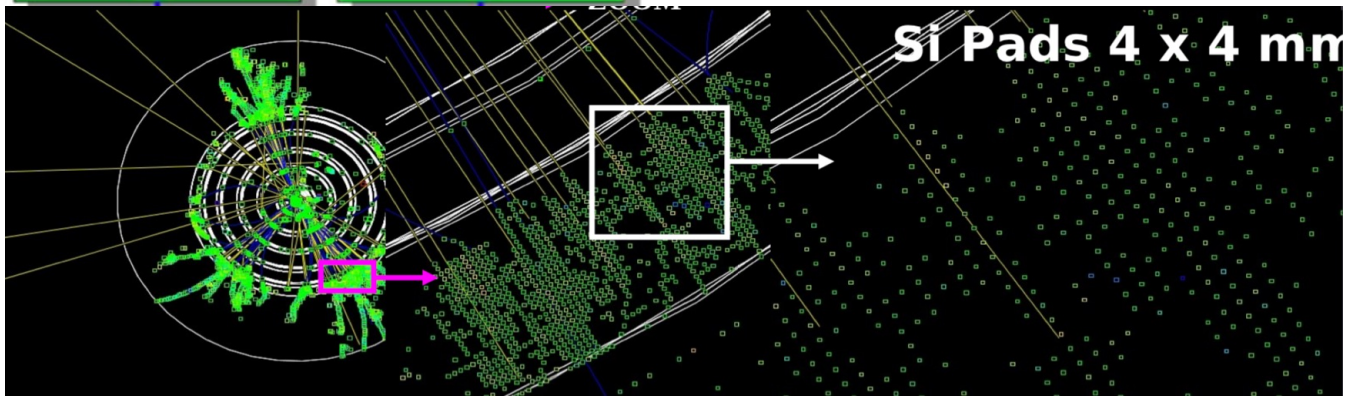




Cross-detector concept R&D

Mainly organised within the: CALICE Collaboration

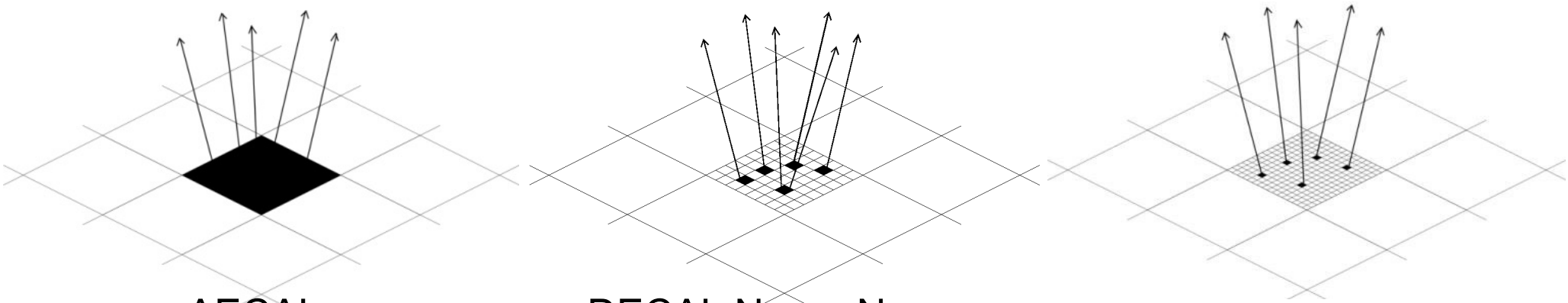




- Particle flow approach → high granularity calorimeter
- How granular? Move from analogue energy deposit to shower particle counting
- (Ultra) high granularity calorimeter
  - Reduce contribution to resolution from Landau fluctuations
  - Very good two-shower separation and position resolution

DECAL Concept for SiW ECAL

- Swap ~0.5x0.5 cm2 Si pads with small pixels
  - at most one particle/pixel, for 1-bit ADC/pixel – binary approach
- Avoid saturation/non-linearity…
  - EM shower core density at 500GeV ~100/mm^2
  - Pixels size <100x100μm^2
  - ~10^{12} pixels for ECAL barrel



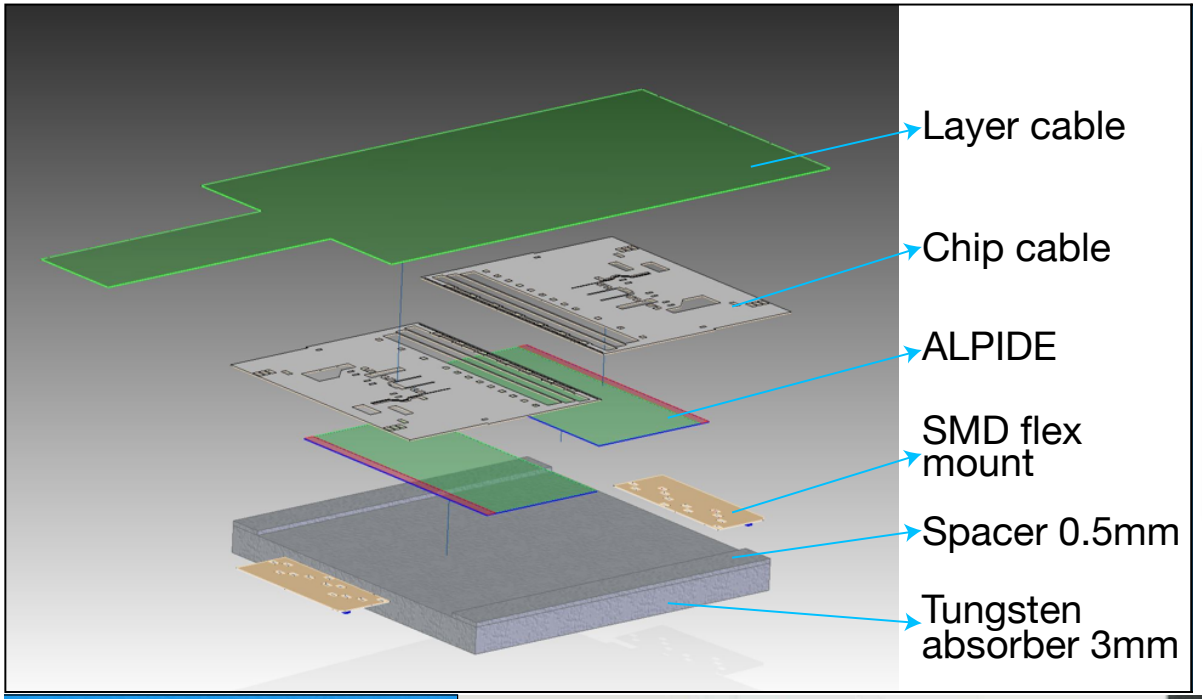
AECAL

DECAL $N_{pixels}<N_{particles}$

saturation / nonlinearity

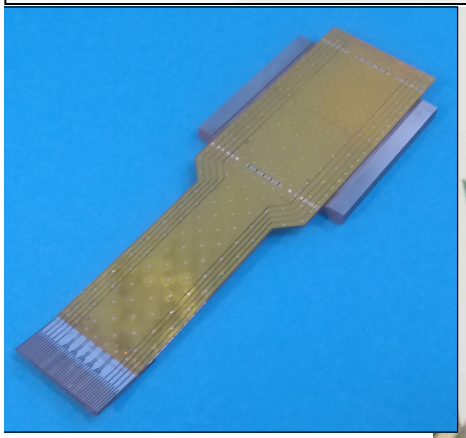
- Simpler construction (no bump bonding)
- DECAL prototypes to date 180 nm process → 65nm
- Performance gains? Tracking highly boosted decays, e.g. $\tau, \pi^0 \rightarrow \gamma\gamma$ …
- Effectively a 'tracking calorimeter'

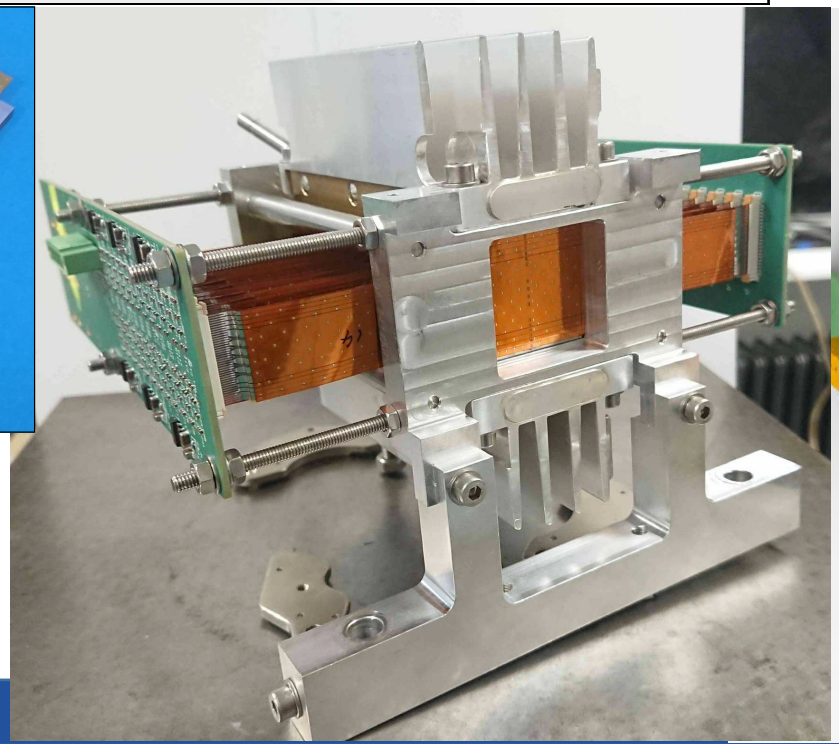
DECAL prototype reality: EPICAL-2

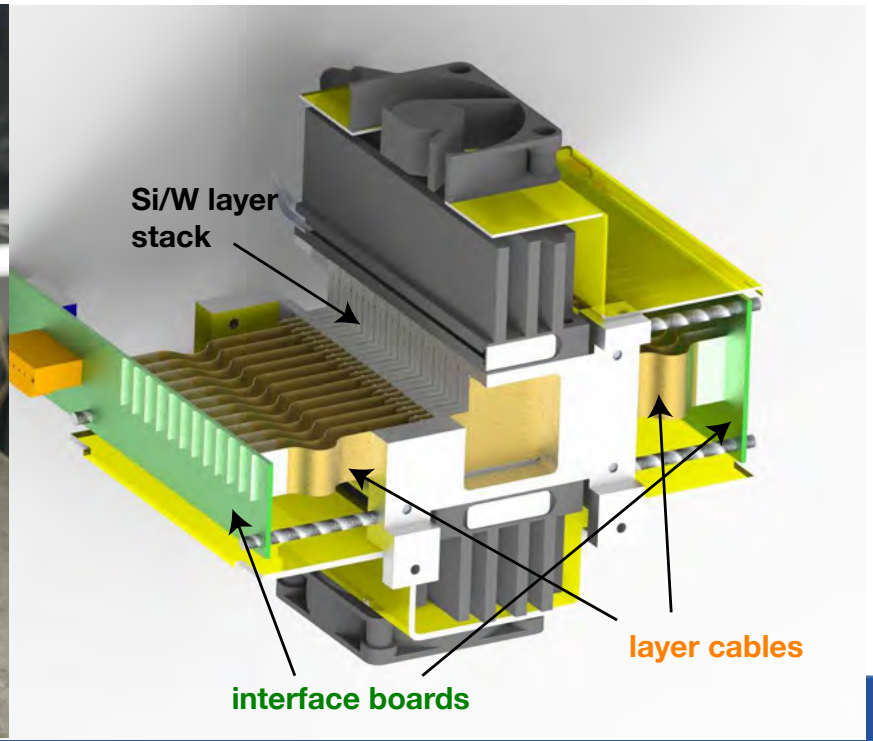


24 layers, each

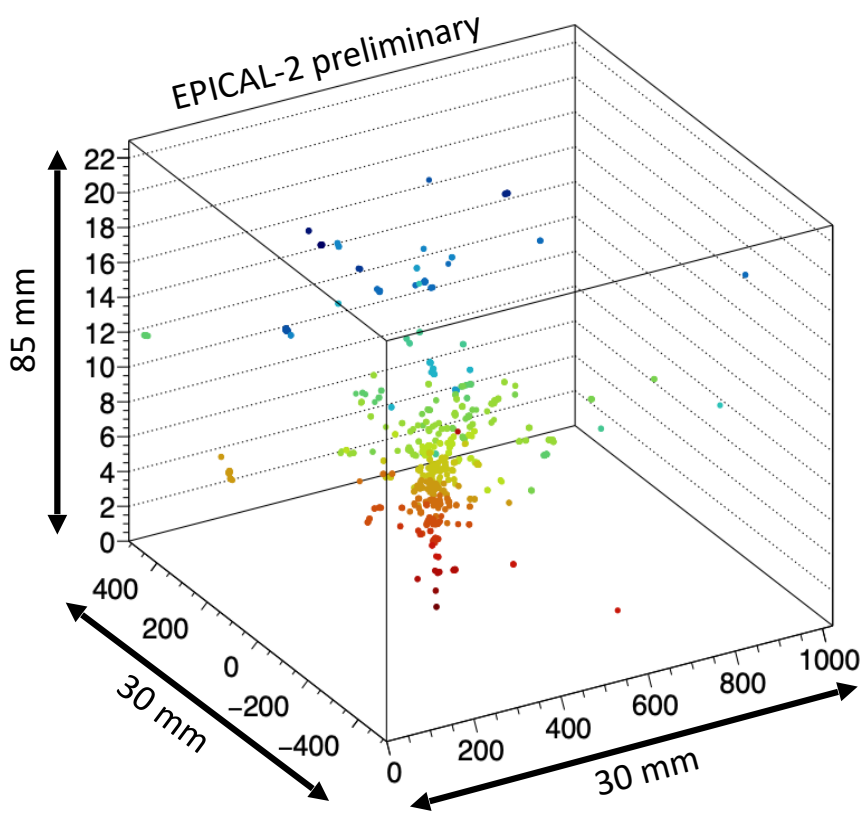
- 3 mm W / 2 ALPIDE CMOS
- 3 x 3 cm^2 active
- 1M (29.24 x 26.88 μm^2) pixels
- ultra-thin flex cables (LTU Kharkiv)
- compact design: expect $R_M \approx 11$ mm



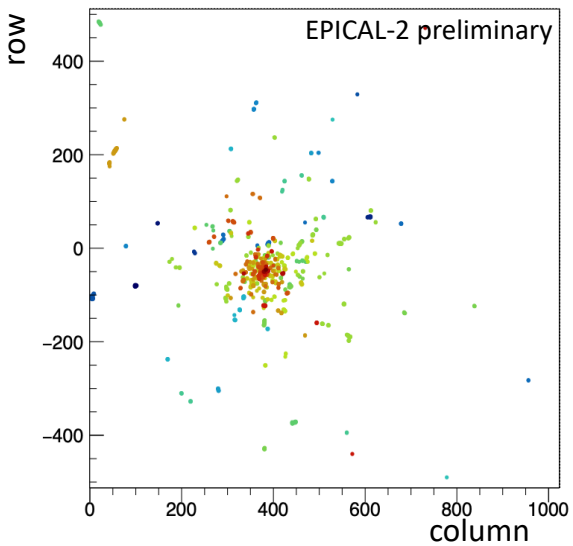


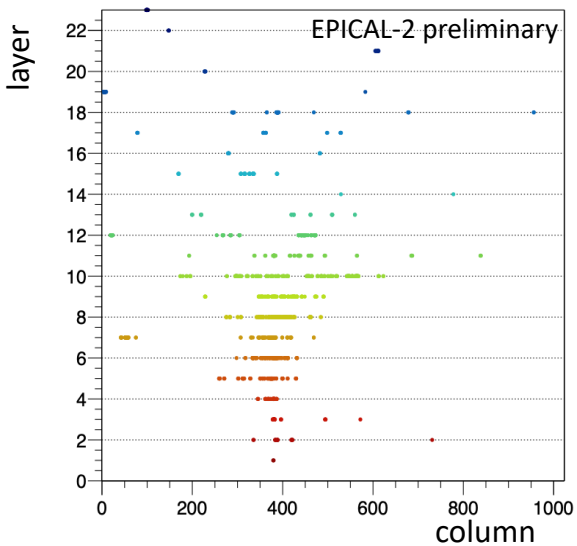


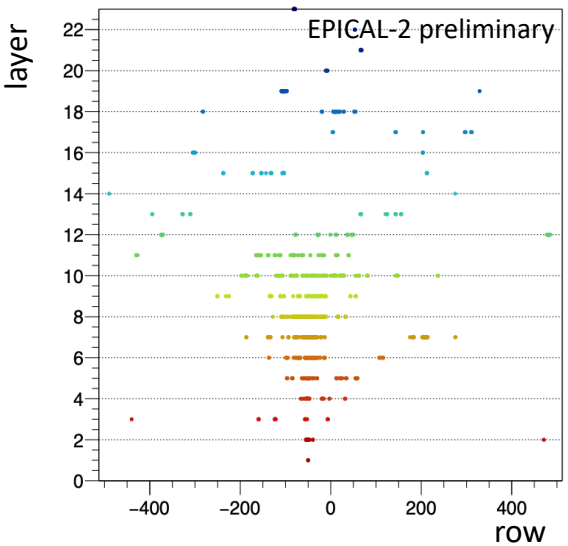
Event Display



one-electron event
5 GeV
raw data



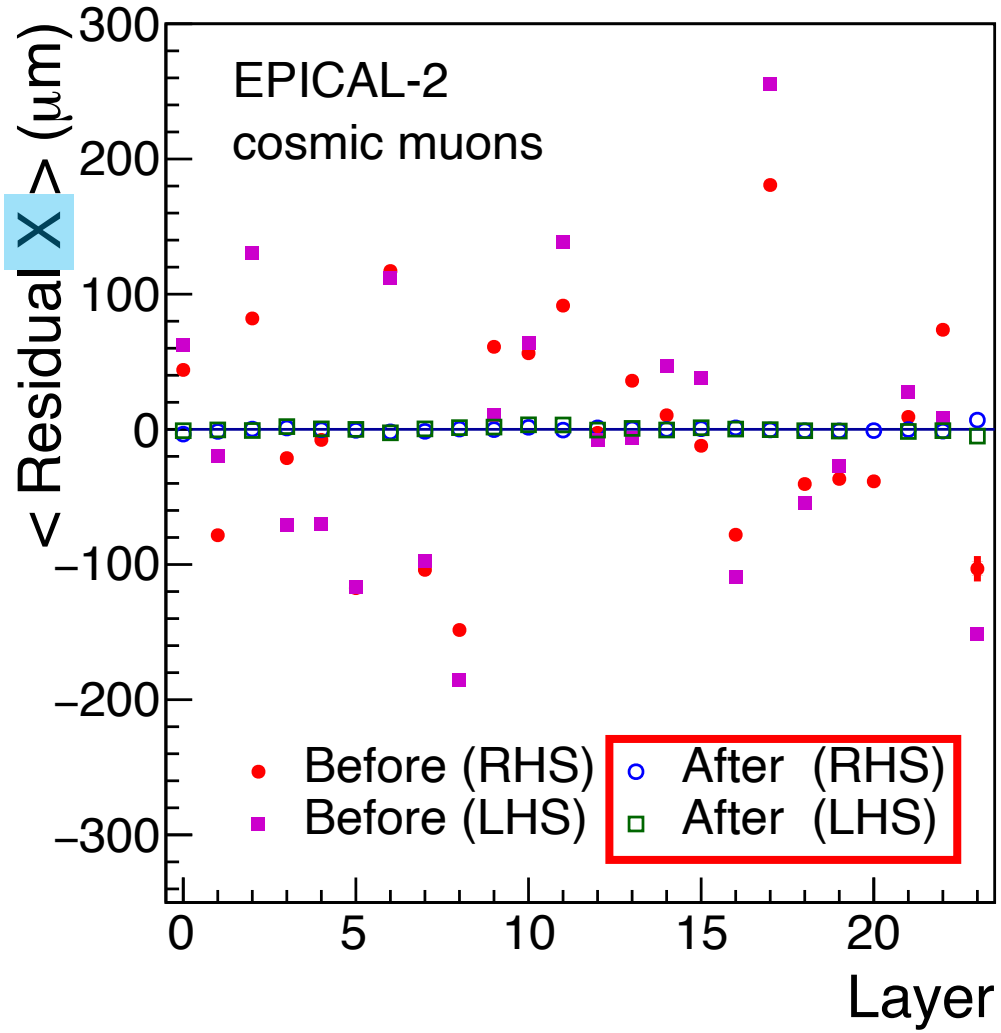


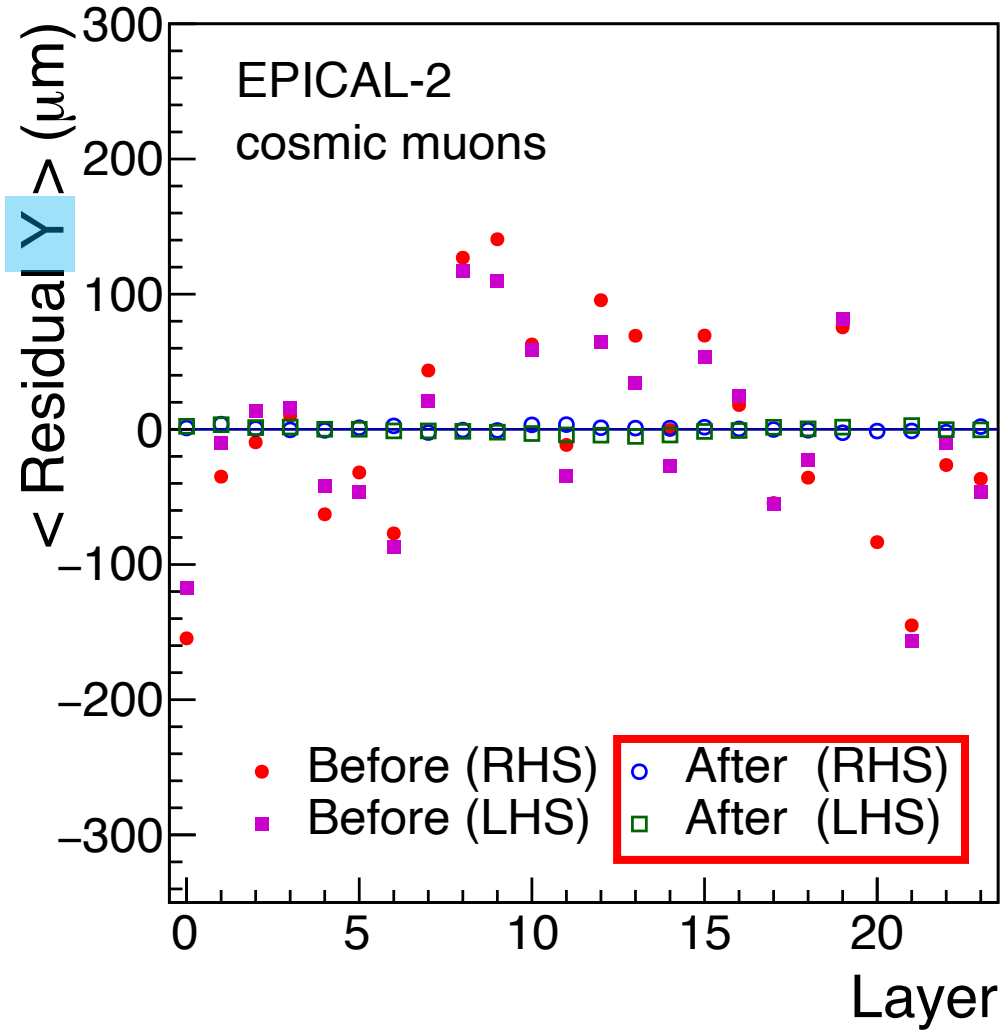


→ **detailed evolution of shower**

color coding: layers

Preliminaries: aligning layers

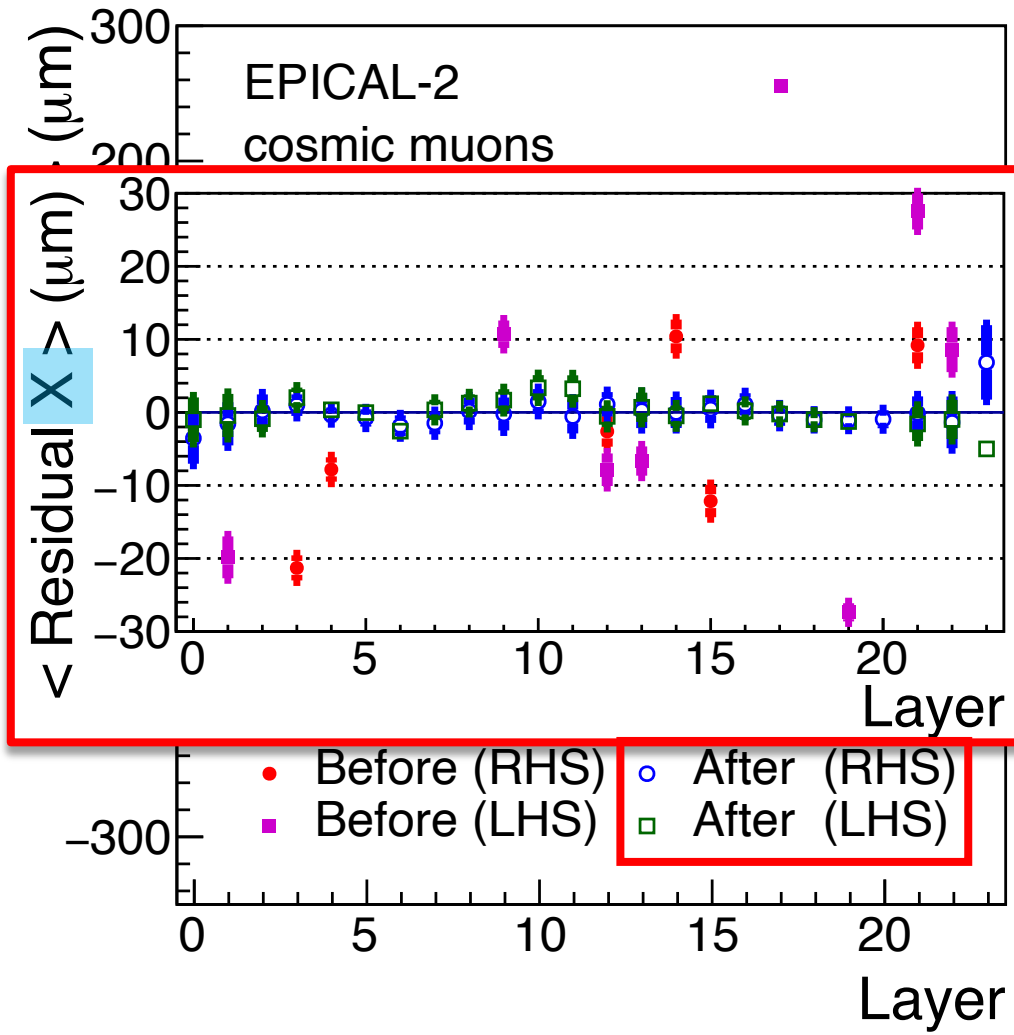


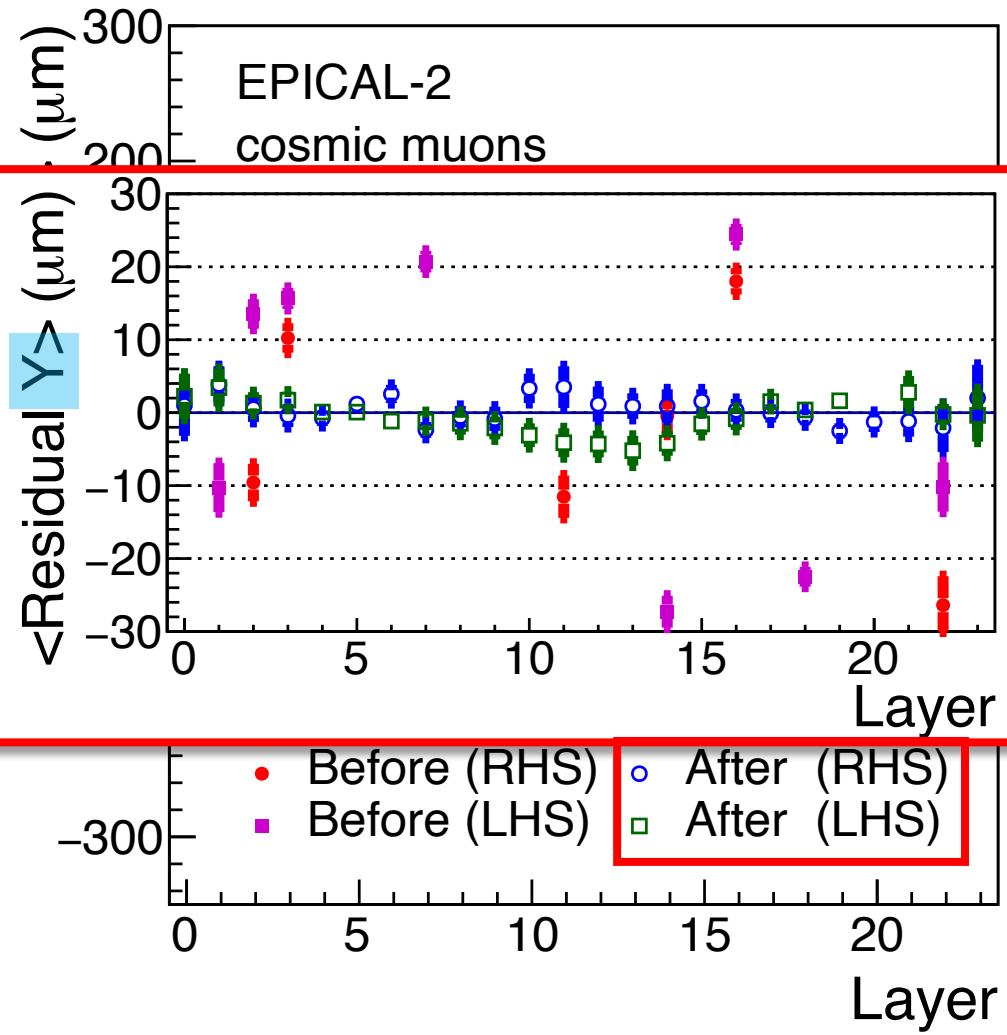


- Selected sample of 5k cosmic muons in lab
- After alignment, residuals < 5μm

[JINST 18 (2023) 01, P01038]

Preliminaries: aligning layers

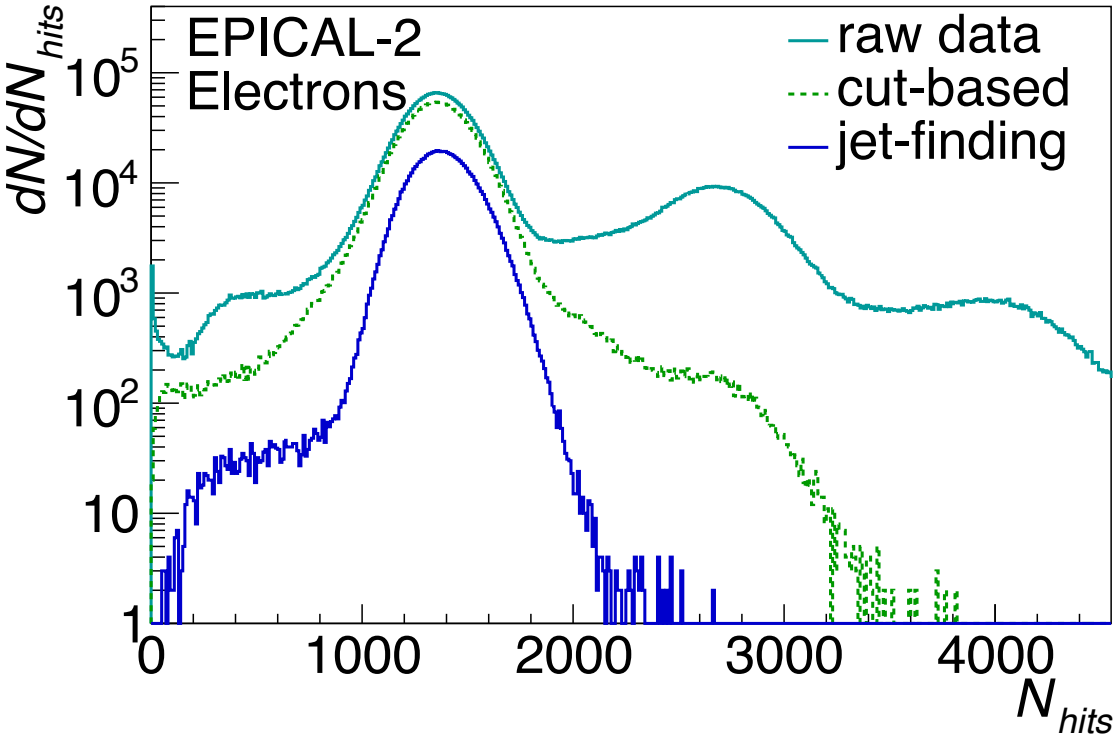




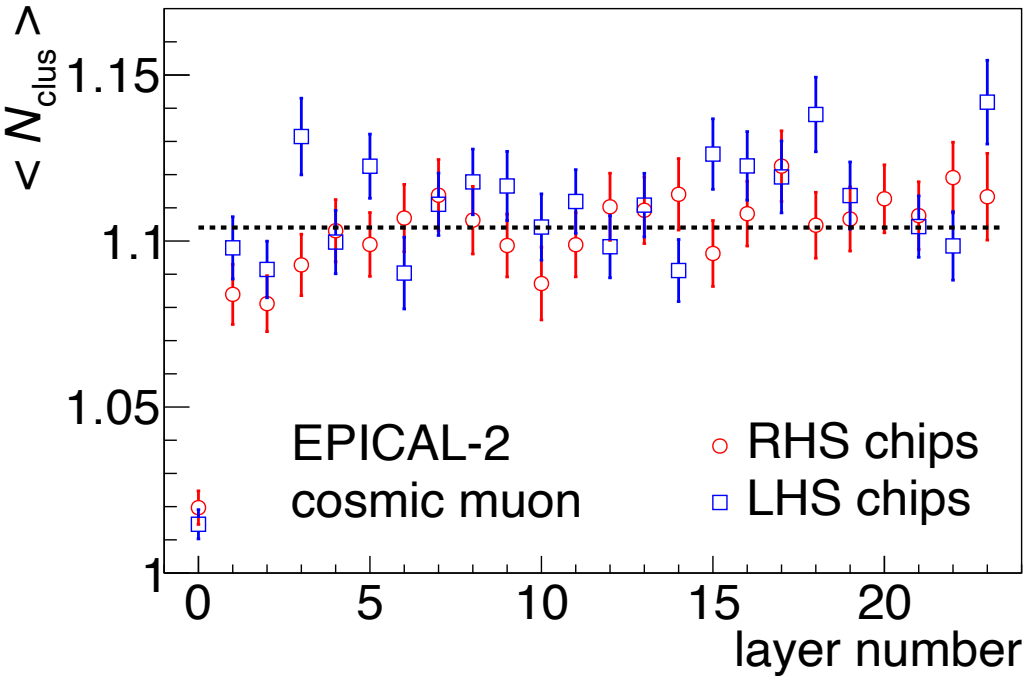
- Selected sample of 5k cosmic muons in lab
- After alignment, residuals < $5\mu m$

[JINST 18 (2023) 01, P01038]

DESY Test beam: 1-6 GeV electrons



- Event selections ensure
  - Lateral containment
  - Single particle showers
- Basic clustering and pixel hits similar



- Calibration of sensors (supply voltage, temperature, FE discriminators) using cosmics
  - Use cosmic muons
  - Separately for hits/clusters
  - Good uniformity (single global threshold/512k pixel sensor)

[JINST 18 (2023) 01, P01038]

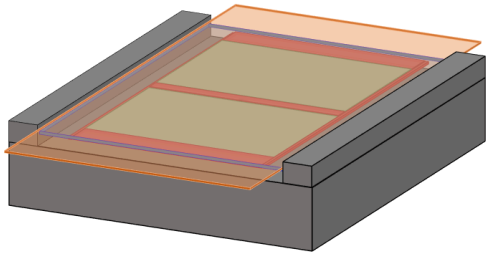
EPICAL-2 simulation utilizing Allpix^2 I

A Monte Carlo simulation tool for silicon pixel detectors
From incoming particle(s) to readout

simulation chain:

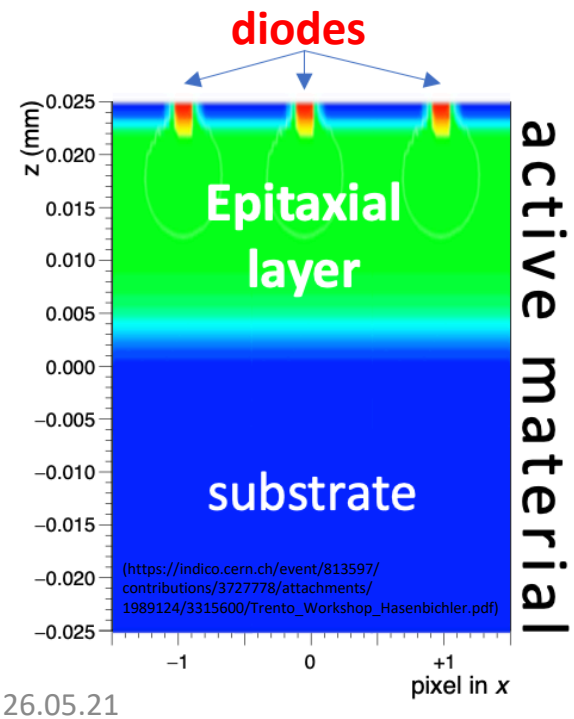
Data modelled well

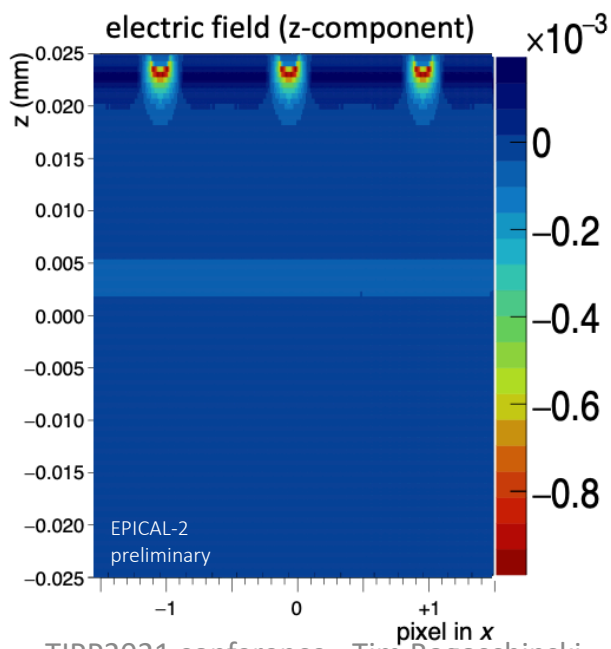
geometry builder → **electric field initialization** → **energy deposition** →

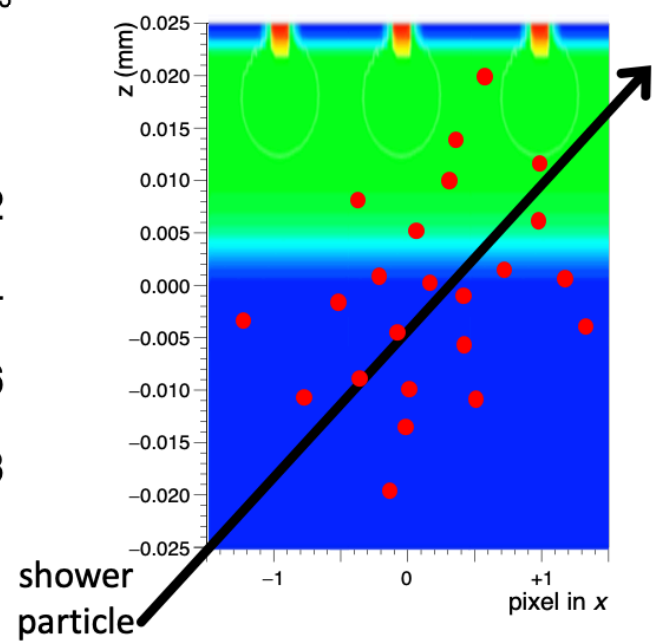


- electric field obtained from **TCAD** simulation by Jan Hasenbichler
- total reverse bias voltage of $V_{RB} = 1.4\ \mathrm{V}$

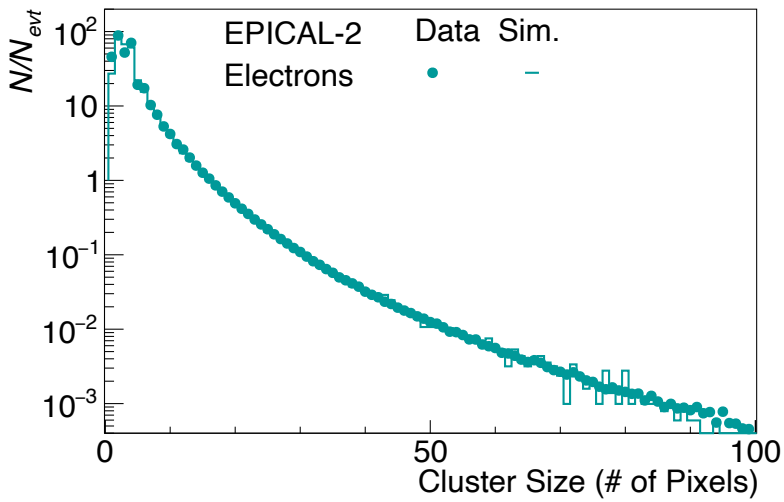
- particle transport and deposition of charges ● in active materials



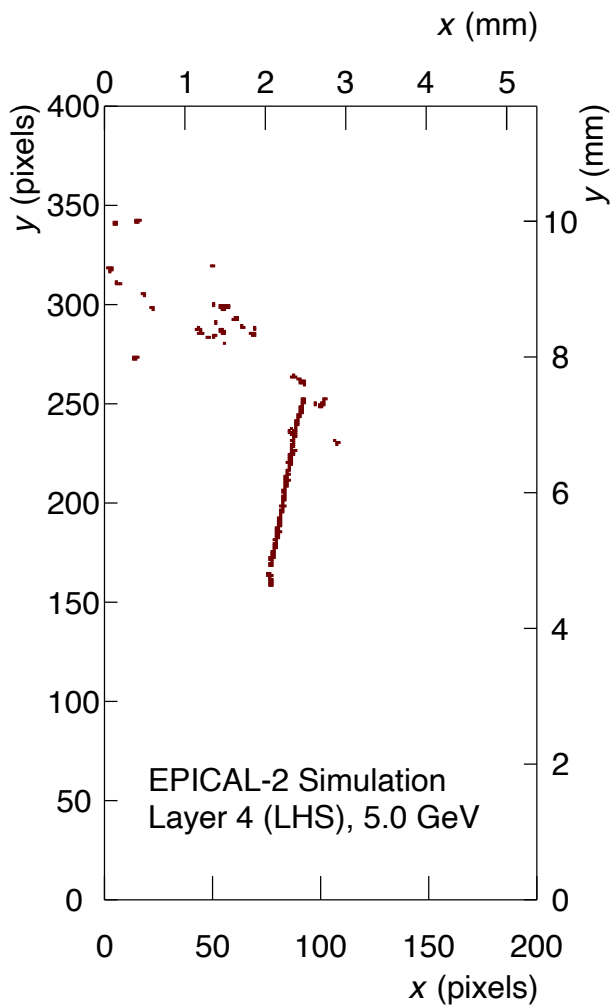


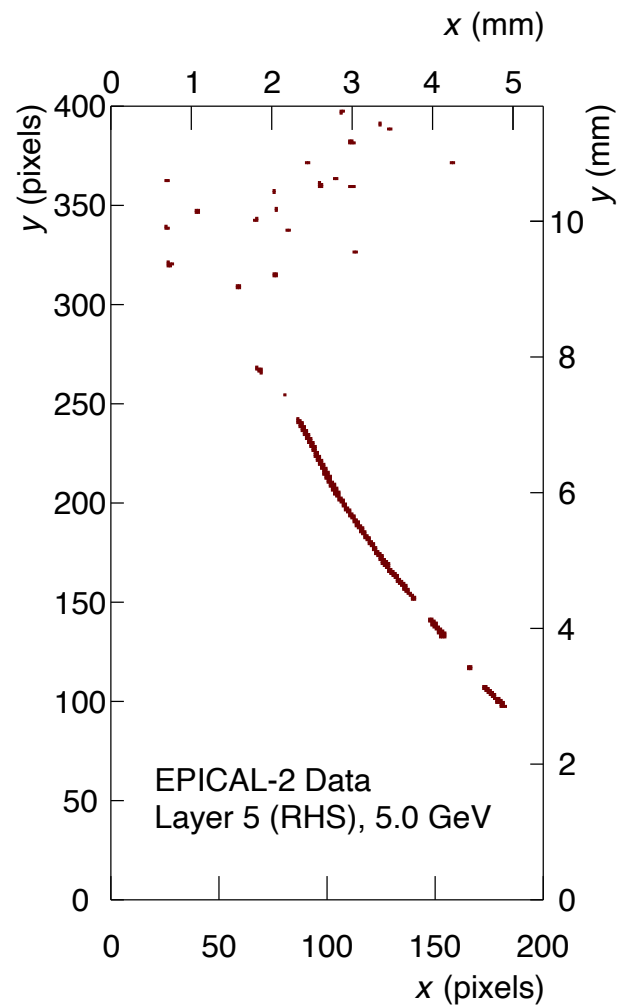


Simulating tails

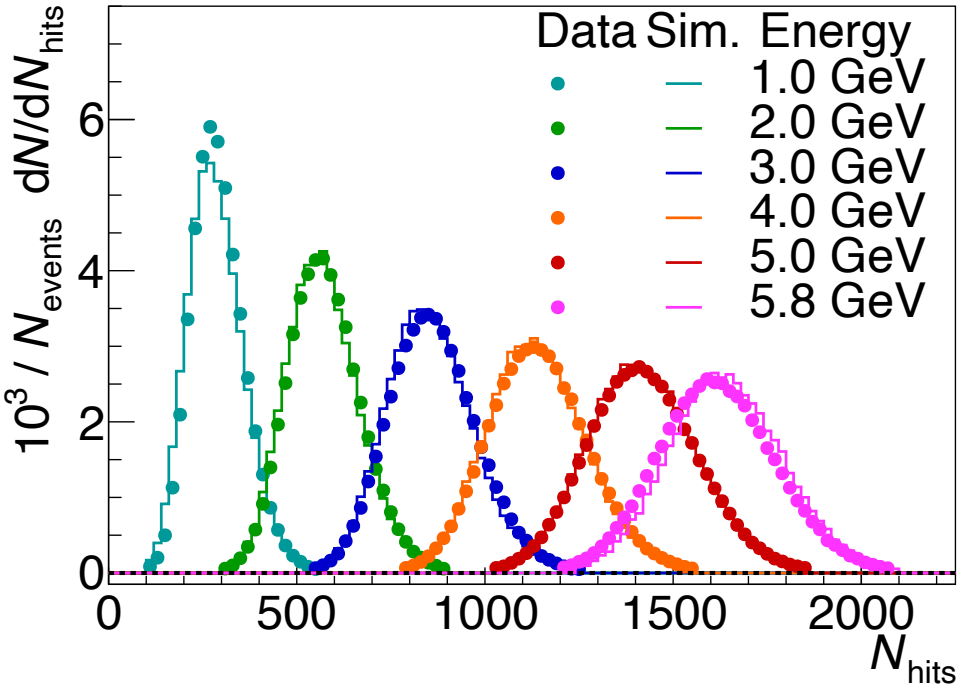


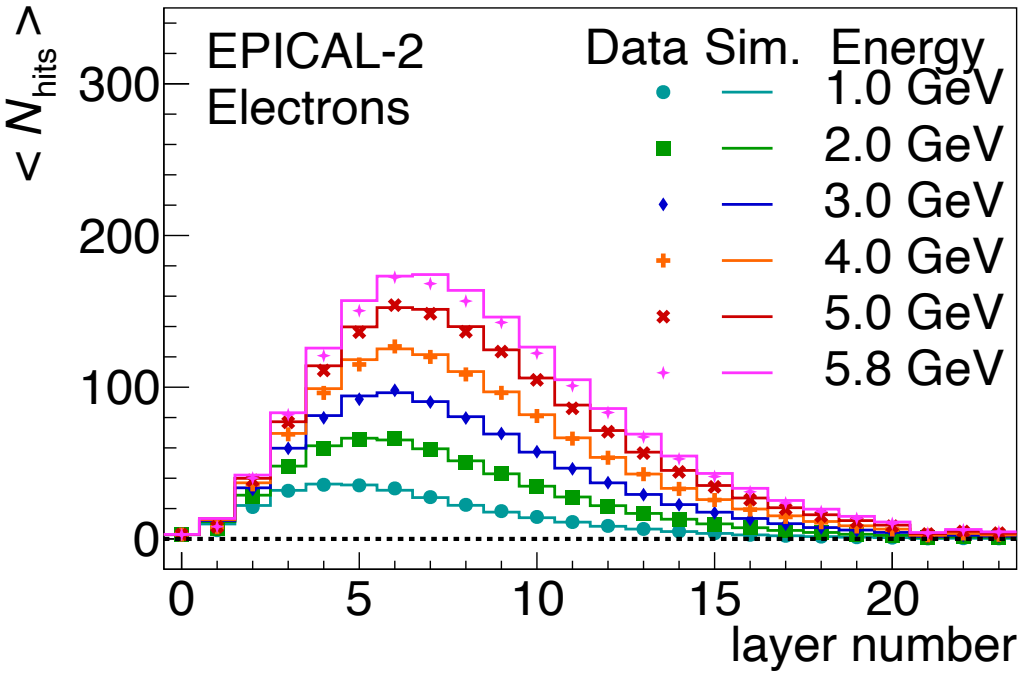
- Simulation models even rare large clusters found in data

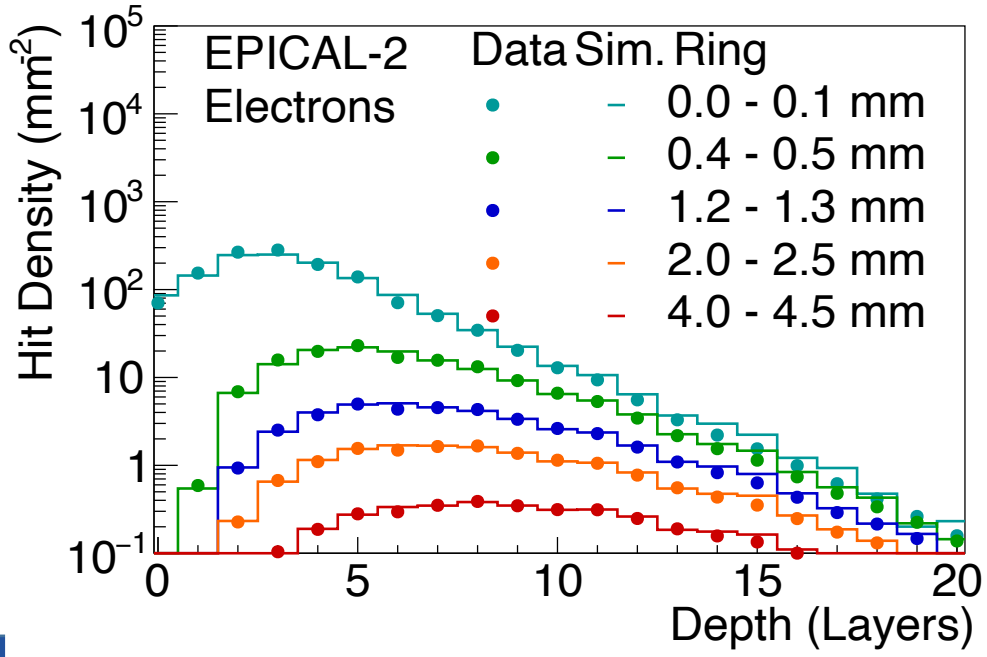




Shower profiles







- Hits and clusters similar
- Described well by AllPix2 simulation

[JINST 18 (2023) 01, P01038]

Energy response fits: details

[JINST 18 (2023) 01, P01038]

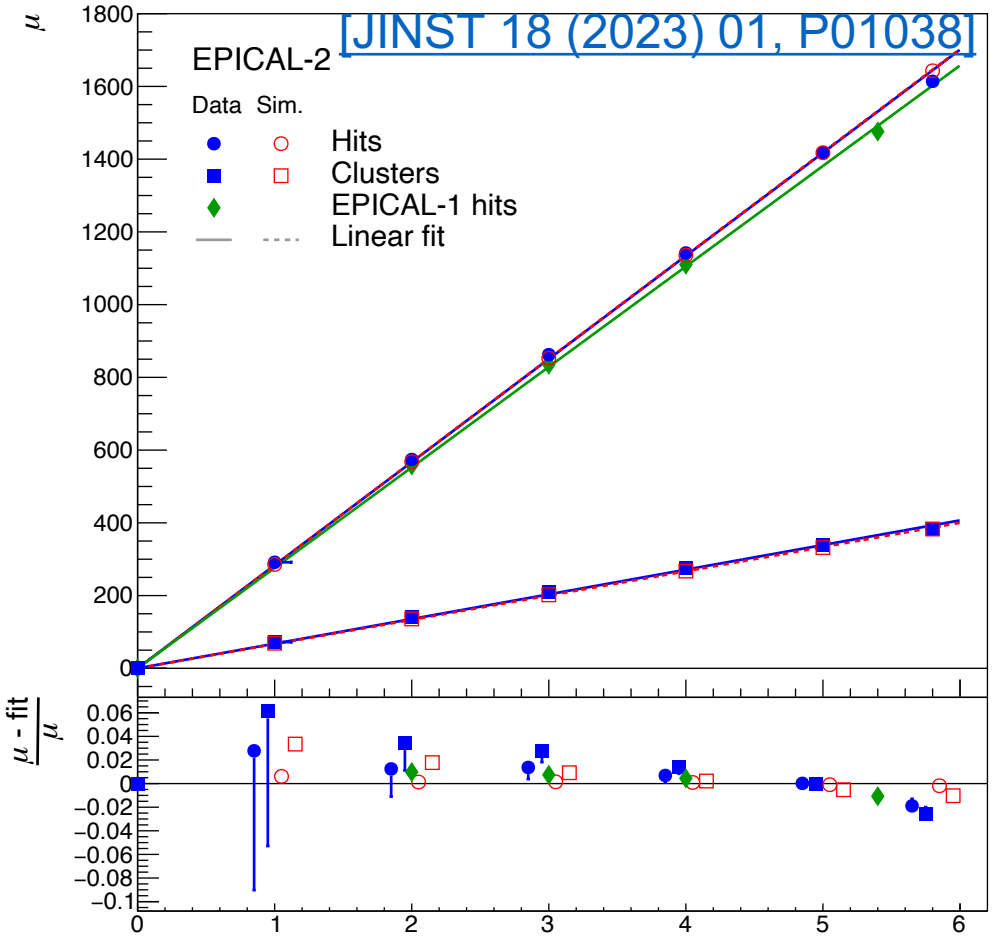
Table 2: Mean μ and standard deviation σ of N_{hits} and N_{clus} distributions in data for electron energies 1.0–5.8 GeV.

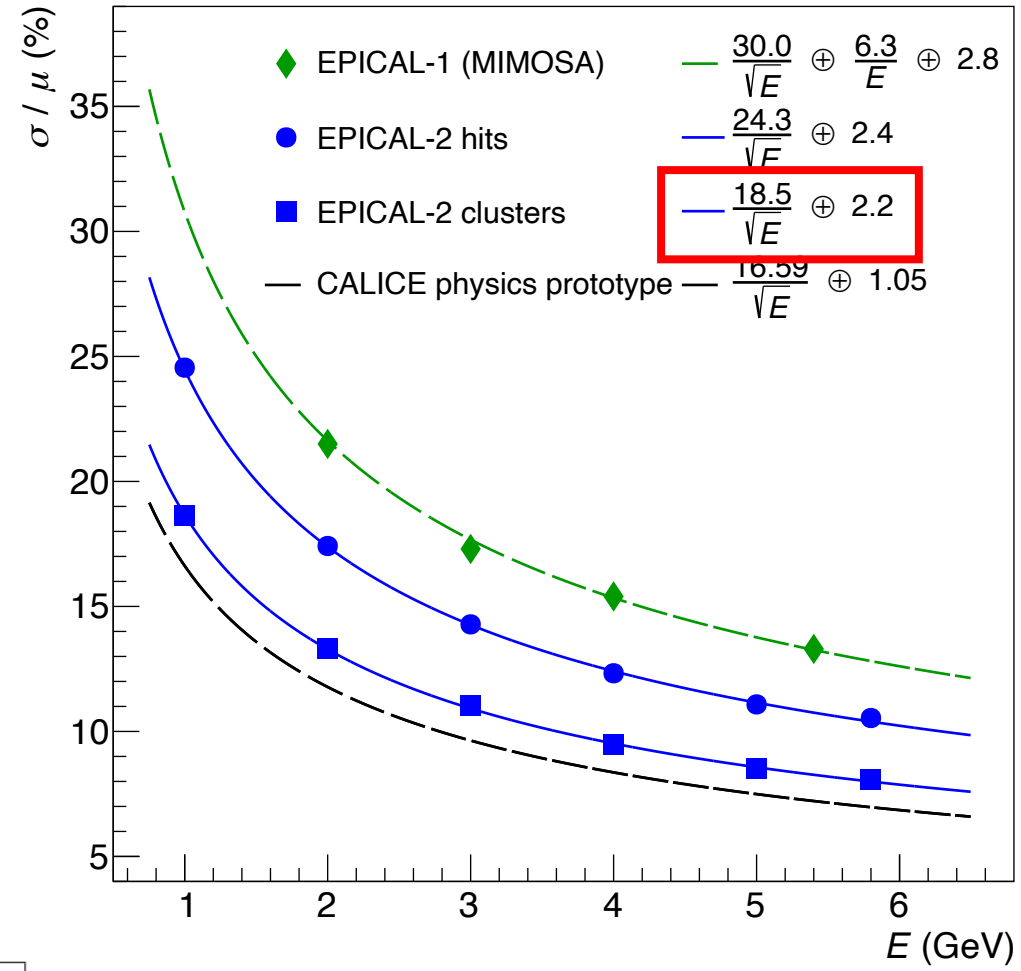
data	hits		clusters	
E_0 (GeV)	μ	σ	μ	σ
1.0	291.63 ± 0.13	71.65 ± 0.09	72.204 ± 0.024	13.467 ± 0.017
2.0	574.17 ± 0.22	100.05 ± 0.16	140.47 ± 0.04	18.718 ± 0.030
3.0	862.39 ± 0.26	123.20 ± 0.19	209.33 ± 0.05	23.072 ± 0.035
4.0	1141.96 ± 0.25	140.80 ± 0.18	275.20 ± 0.05	26.099 ± 0.033
5.0	1417.88 ± 0.20	157.14 ± 0.14	339.04 ± 0.04	28.843 ± 0.025
5.8	1613.99 ± 0.29	170.08 ± 0.20	383.36 ± 0.05	30.99 ± 0.04

Table 3: Mean μ and the standard deviation σ of the N_{hits} and N_{clus} distributions in simulation for electron energies 1.0–5.8 GeV.

simulation	hits		clusters	
E_0 (GeV)	μ	σ	μ	σ
1.0	286.20 ± 0.32	75.48 ± 0.22	69.52 ± 0.06	14.50 ± 0.04
2.0	568.8 ± 0.4	96.71 ± 0.30	136.34 ± 0.08	17.41 ± 0.05
3.0	853.1 ± 0.5	116.11 ± 0.35	202.50 ± 0.09	20.21 ± 0.06
4.0	1136.7 ± 0.6	131.4 ± 0.4	267.93 ± 0.10	22.57 ± 0.07
5.0	1418.1 ± 0.6	145.6 ± 0.5	332.33 ± 0.11	24.66 ± 0.08
5.8	1643.5 ± 0.7	155.7 ± 0.5	383.50 ± 0.12	26.25 ± 0.08

Calorimetric performance





hits	a (%)	b (%)	c (%)
data	24.30 ± 0.03	2.41 ± 0.08	-
sim ($E_{\text{spread}} = 0$)	21.27 ± 0.06	2.30 ± 0.16	-
sim ($E_{\text{spread}} = 158\,\text{MeV}$)	21.58 ± 0.25	1.8 ± 0.5	15.1 ± 0.4
clusters	a (%)	b (%)	c (%)
data	18.54 ± 0.02	2.17 ± 0.05	-
sim ($E_{\text{spread}} = 0$)	14.10 ± 0.04	2.52 ± 0.07	-
sim ($E_{\text{spread}} = 158\,\text{MeV}$)	14.57 ± 0.21	1.96 ± 0.26	14.93 ± 0.23

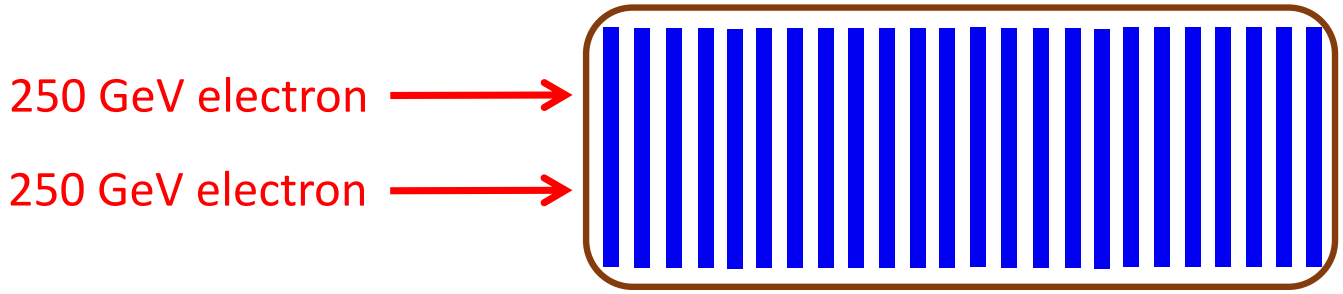
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus b \oplus \frac{c}{E/\text{GeV}}$$

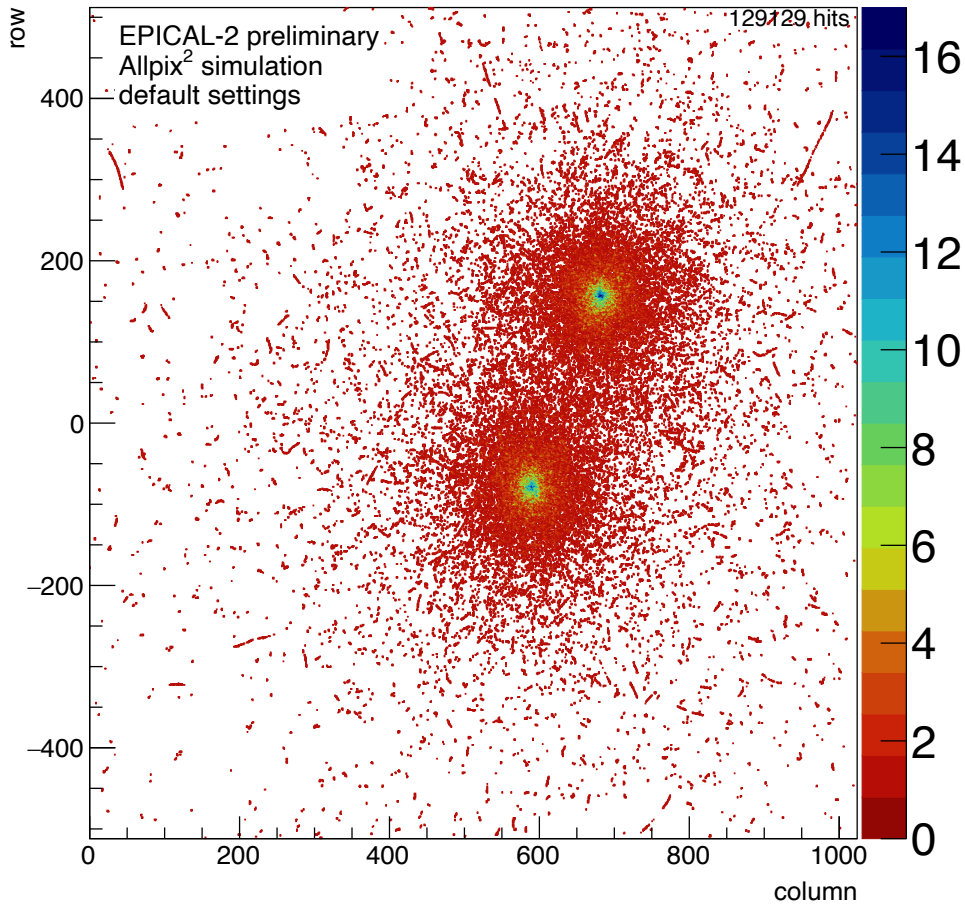
- Good standard performance
- Better resolution from clusters
- Uncertainties in beam energy spread

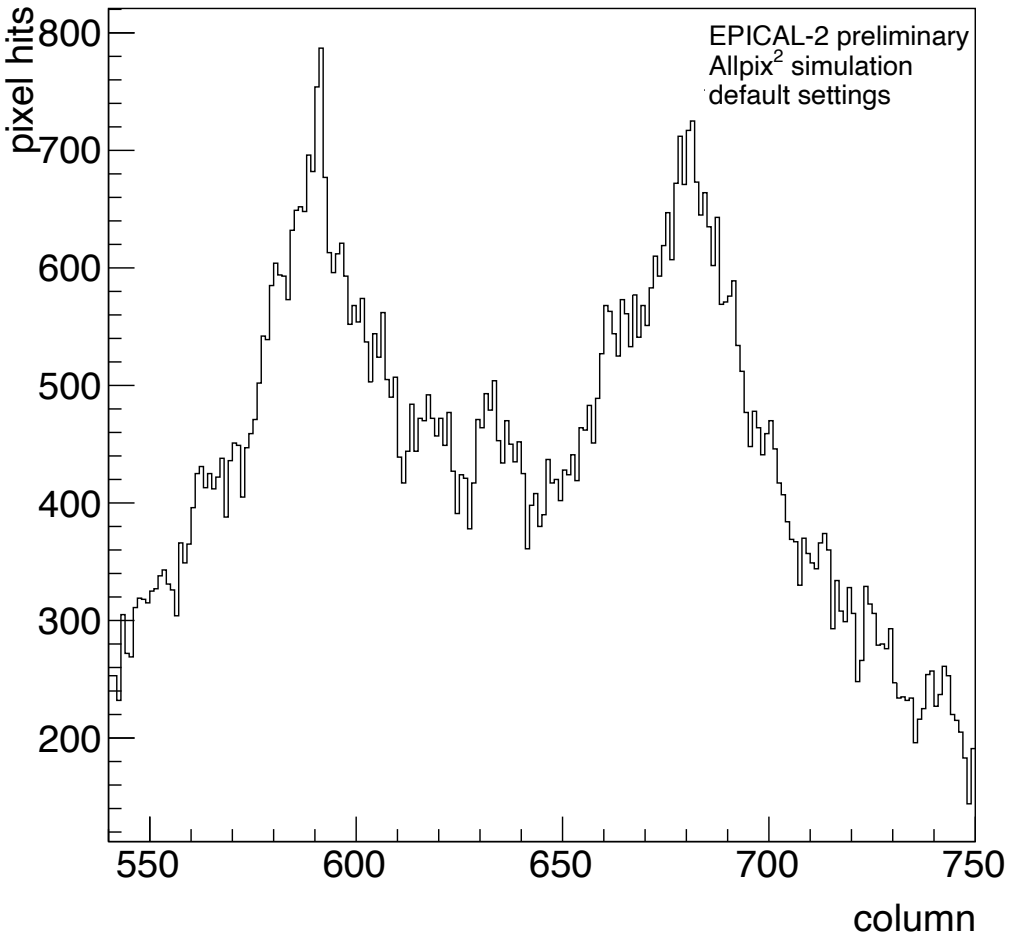
Benefit of ultra-high granularity

separation power

- same energy
- electrons separated by $\sim 7.2\ \mathrm{mm}$







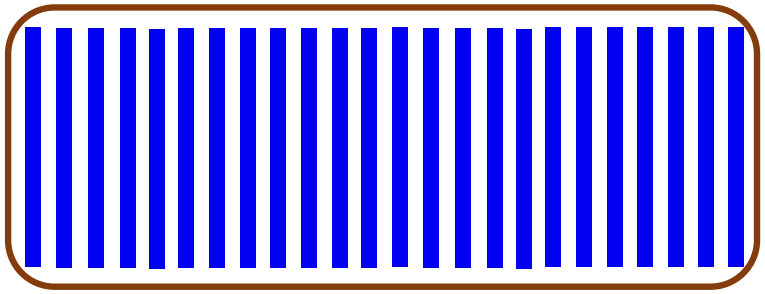
Benefit of ultra-high granularity

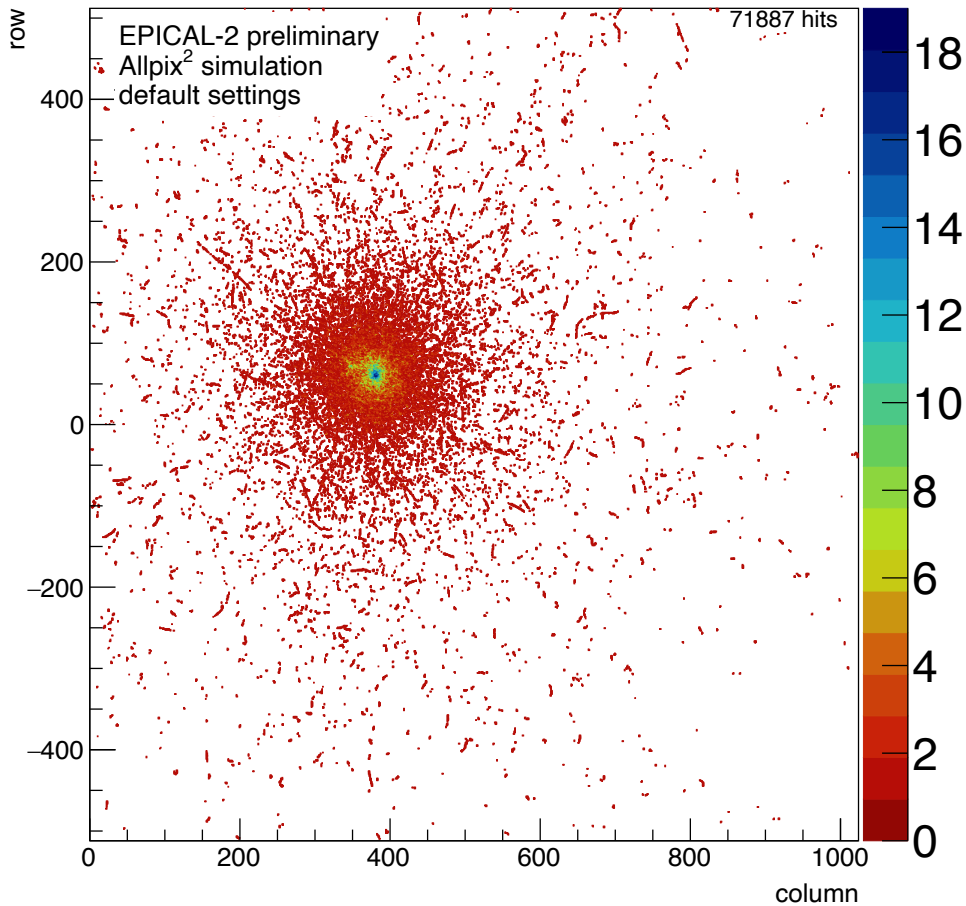
separation power

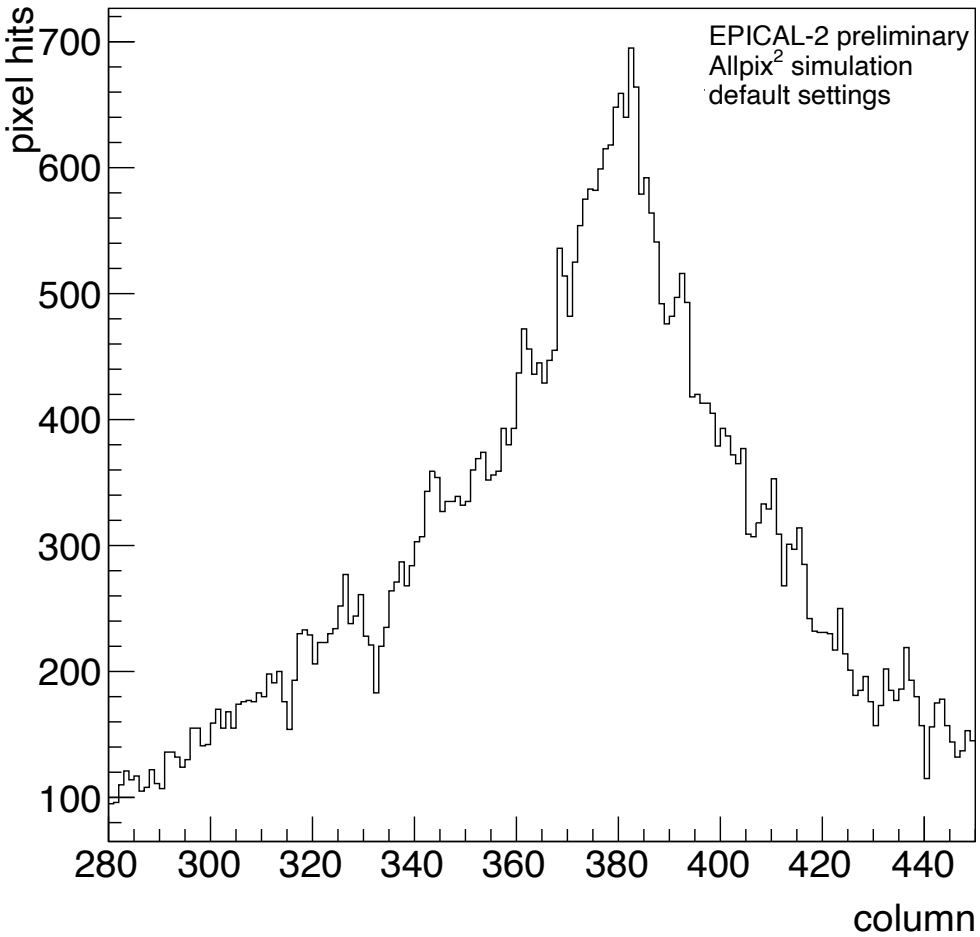
- large energy difference
- electrons close together

→ **challenging case**

250 GeV electron →
30 GeV electron →







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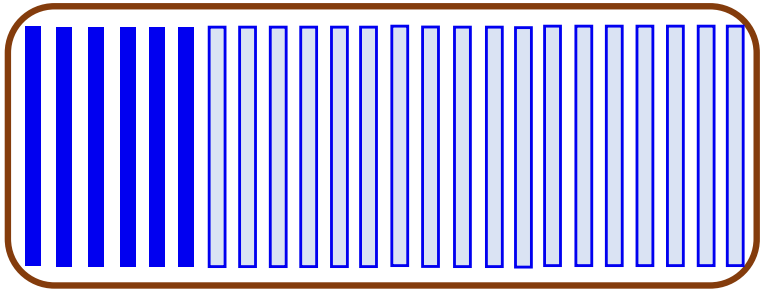
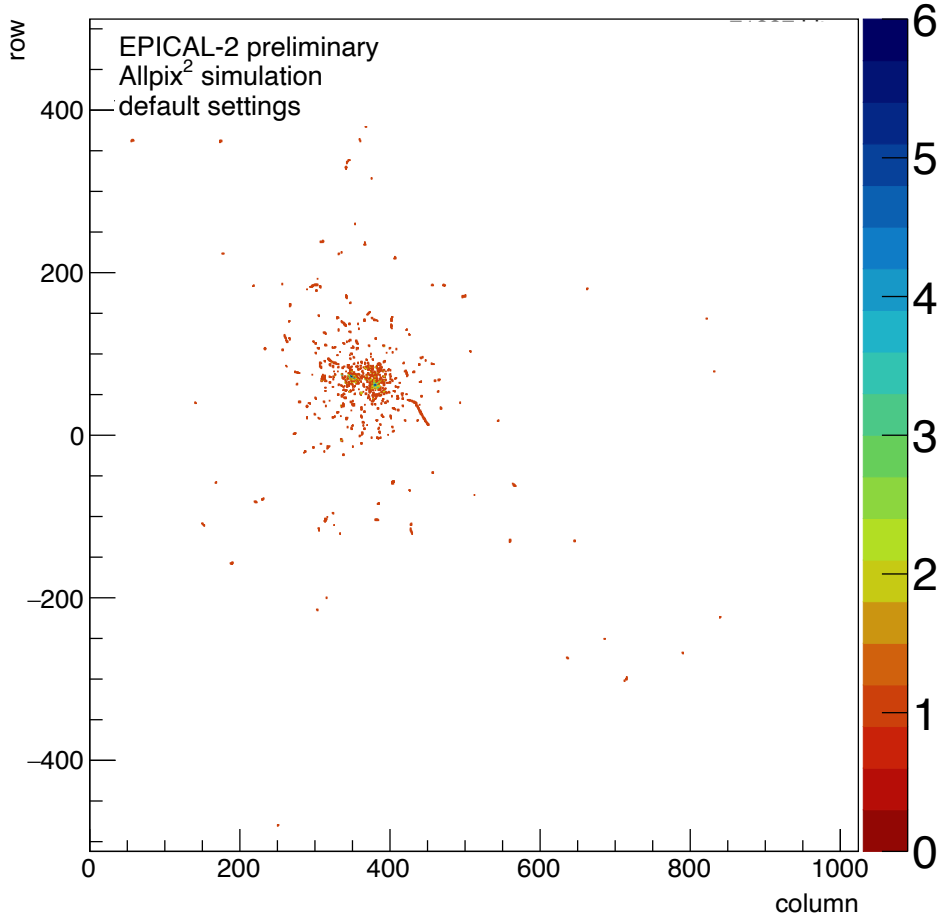
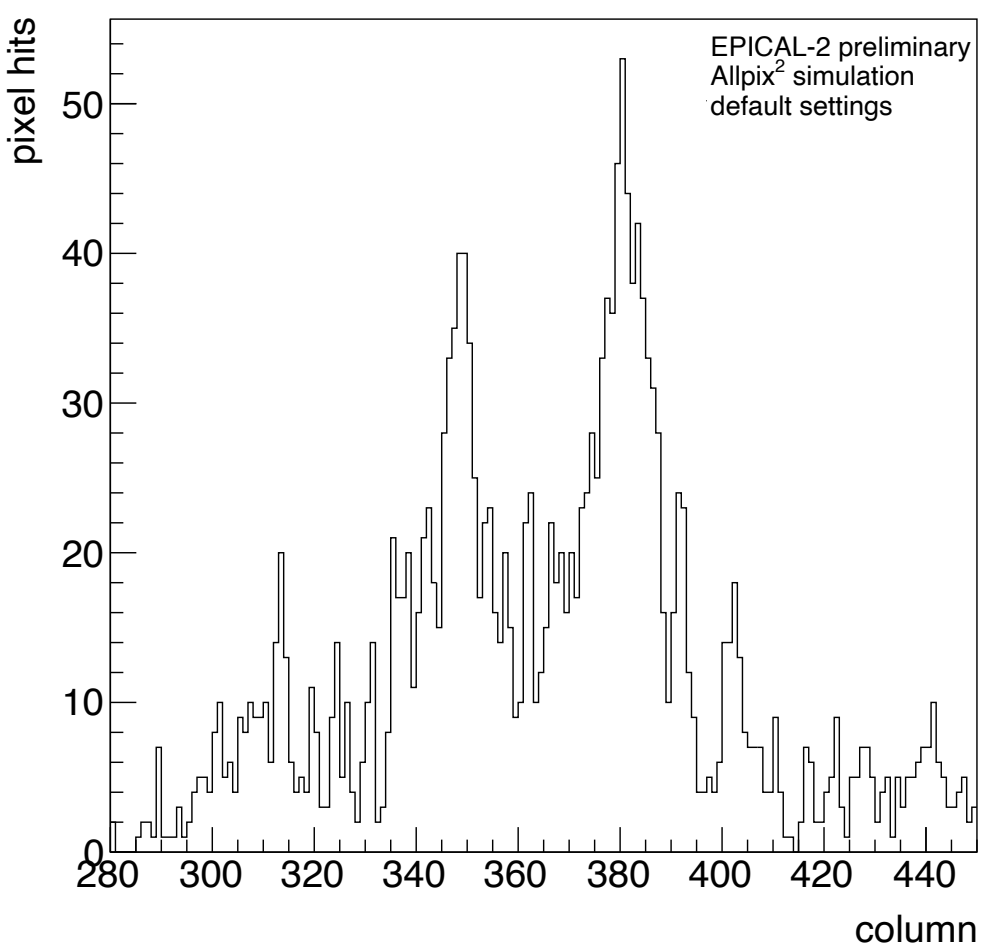






Future Opportunities for DECAL

- **Si-W calorimetry can give excellent PFA performance**
  - Potential for reconfigurable technology: outer tracker/preshower/ECAL
    - I.Kopsalis et al, NIM A1038 (2022) 166955
    - P.P.Allport et al, Sensors 2022, 22(18) 6848
- Affordable Si-W calorimeters, sensors ~ CHF/cm^2 (active areas > 10^7cm^2)
  - Potentially achievable with CMOS MAPS
- Power needs study, CMOS estimates range ~50-100mW/cm^2 (no pulsing)
- Prototype demonstrating concept of digital ECAL, in same CMOS line as CERN et al, can deliver radiation hardness to > 10^{15}neq/cm^2
- **Digital EM calorimetry, high potential esp. for future e^+e^-**
  - Ultra-high granularity can benefit physics as well as cost (boosted decays)
  - Calorimetric performance demonstrated
  - Existing data with EPICAL-2 up to 80 GeV / SPS (analysis in progress)
  - Enhance with optimised sensor development
  - ECFA DRD proposal and interested in collaborate widely ☺

[Thanks to Roman Poeschl, Tim Rogoschinki, Thomas Peitzmann and others!]

backup

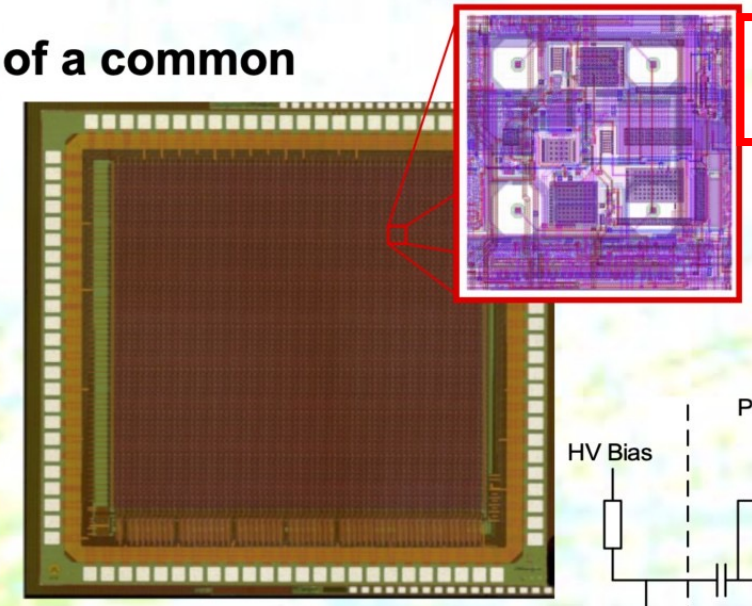
DECAL (4mm×4mm Array) Prototype Chip

Concept in FCC-hh context of a common silicon development for:

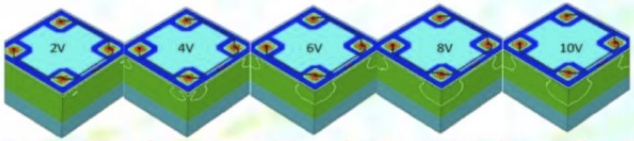
- **Outer tracking**
- **Pre-shower**
- **EM calorimeter**

Reconfigurable sensor as:

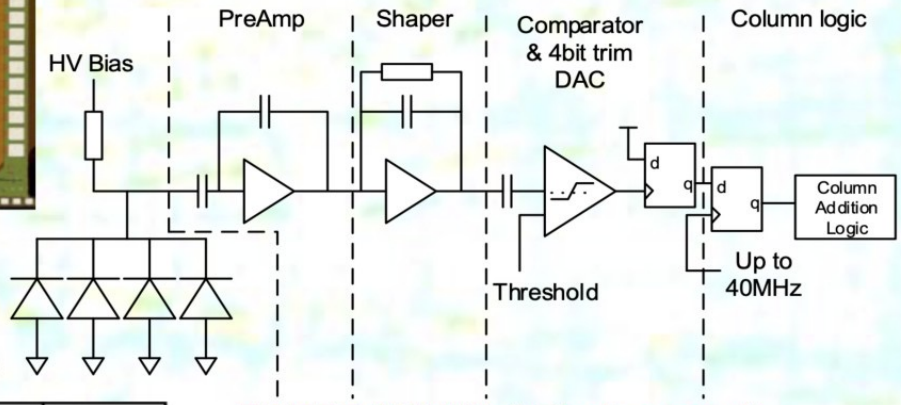
- **5mm×50μm strips**
- **5mm×5mm pad**



opportunities



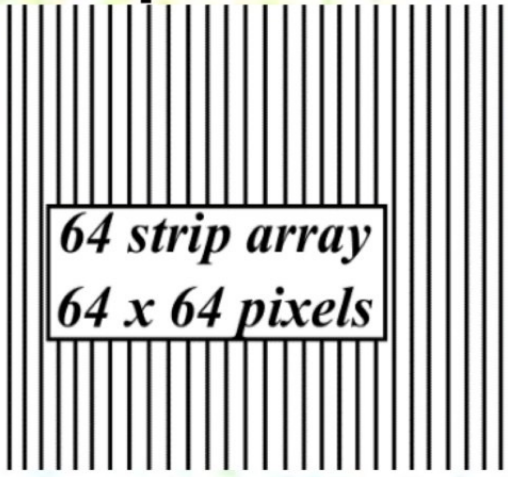
4 Diode TCAD Simulation: Giulio Villani



TWEPP (4/9/19) S.Benhammadi

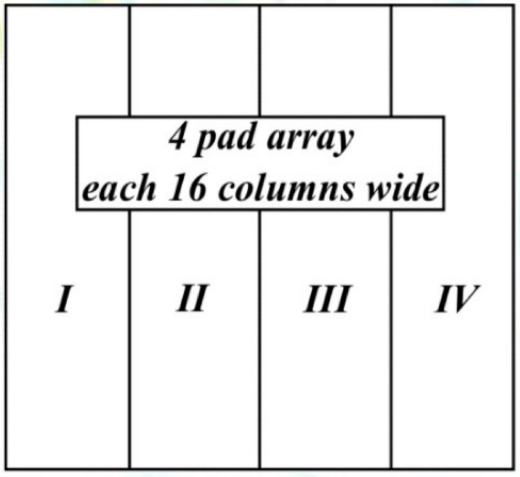
Prototype as proof of concept (180nm CMOS*)

Strip mode



Information on up to 3 hits per column gives data rate 5.12Gb/s

Pad mode



Information on up to 15 hits per column giving 240 hits per pad gives data rate of 2.56Gb/s

Specification	*Unit*	*Value*
Pixel Pitch	um	55
Resolution	pix	64 x 64
Frame Rate	MHz	40
Input Referred Noise	e- rms	80
Max hits/col (pad mode)	hits	15
Max hits/col (strip mode)	hits	3

***TowerJazz (Small collecting node)**